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Protection, Control and Operation of Transformer Using Numerical Relay

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***Abstract*- This paper explains about the faults occurring in transformer, fault withstand capability of transformer and numerical relays used for protection against fault. Numerical relay can be used to operate, control and protect the transformer used in power system.**

***Index Terms*—ETAP model, short circuit study, CT connection for restricted earthfault, protection setting**

I. INTRODUCTION

Numerical relay protects transformers from fault, controls the transformer and allows the operator to operate the transformer through PMS, SCADA, etc. Numerical relays have the following advantages over traditional electromechanical relays.

- Numerical relays are compact and are more reliable.
- One numerical relay can provide multiple protections to transformer.
- The VA burden of numerical relay is small compared to electromagnetic relay. So current transformers (CTs) with lower VA rating can be used.
- When electromechanical relays are used, three sets of CTs are required for metering/protection and differential function. While numerical relays can take care of all these function with only one set of CTs.
- Numerical relay can communicate the fault status and Circuit Breaker (CB) open/close status to PMS (Power Management System) / SCADA (Supervisory Control And Data Acquisition). The communication protocols available such as MODBUS TCP/IP, profinet, Ethernet / IP, IEC 61850, etc.
- Through PMS / SCADA numerical relay can open/close the CB used to operate the transformer.
- Numerical relay can measure current in all phases, voltage in all phases, power consumption in all phases, power factor, frequency, etc. No separate CTs or PTs are required for measuring electrical parameter. The CTs and PTs used for protection are sufficient for measuring these electrical parameters.
- Numerical relay can communicate the measured electrical parameters (current, voltage, power, etc.) to PMS / SCADA.
- Operation Logic can be built in Numerical relay and these logics can be used to control the operation of transformer.

The input and outputs from numerical relays are as follows

- CT input (current input)
- Potential transformer (PT) input (voltage input)

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- Digital input (potential free contacts from other equipment are hardwired to numerical relay for providing status input)
- Digital output (potential free contacts of numerical relay are hardwired for controlling, interlocking, tripping of breaker, etc.)
- RTD input.
- Serial link communication I/O port
- Relay settings (time setting multiplier, pickup setting, etc.)
- Logic diagram.

The hardware structure is discussed in Section II. The protection function provided by numerical relay is discussed in Section III to X. Control and operation features are discussed in Section XI.

II. HARDWARE STRUCTURE OF NUNERICAL RELAY

Numerical relay receives input, processes the input value, provides desired output, records the I/Os and communicates the recorded/calculated values using the following module (refer Fig. 1 & Fig. 2).

- CT and PT input module
- Digital input module
- Digital output module
- HMI or MMI module
- Communication interface module
- Microprocessor module
- Power supply module

A.CT and PT Input Module

The external CTs and PTs are connected to CT and PT input module. The CT and PT input module consists of internal CTs and PTs for converting the current (from external CTs) and voltage (from external PTs) to the internal processing values. For example the internal CT (inside CT and PT module) converts 5A to internal processing value of 1A.

B. Digital Input Module

External potential free contacts wetted with DC source are connected to digital input module. Normally the DC source has the voltage of 110V or 48V or 24V. When the potential free contacts are closed the digital input module receives DC source voltage and when the potential free contacts opens the digital input module receives 0V. Hence the external digital signal has 0 and 110V, 0 and 48V, etc.

Digital input module consists of optical coupler for converting external digital signal to the internal processing values. For example, Optical coupler converts digital signal of 0 and 110V to digital signal having 0V and 5V i.e. when external signal is 0V, optical coupler output will be 0V and when the external signal is 110V, optical coupler output will be 5V.

Also optical coupler provides isolation between the external circuit and internal microprocessor module. Hence any abnormalities like over voltage, current, etc. in external circuit doesn’t damage the microprocessor module.

C. Digital Output Module

Digital output module consists of relays with potential free contacts and coil. These relay coils are energised to close (NO contact) or/and open (NC contacts) the potential free contact. These contacts are operated by the microprocessor module. These contacts are used to open the breaker, close the breaker, trip the breaker, provide interlocks and provide status input to other equipment.

D. HMI or MMI Module

HMI (Human Machine Interface) or MMI (Man Machine Interface) module consists of LCD display and keyboard. The keyboard is used to feed the input to numerical relay like relay setting, date & time, communication gateway, etc.

The LCD display shows the electrical parameters measured, alarm status, fault status, etc.

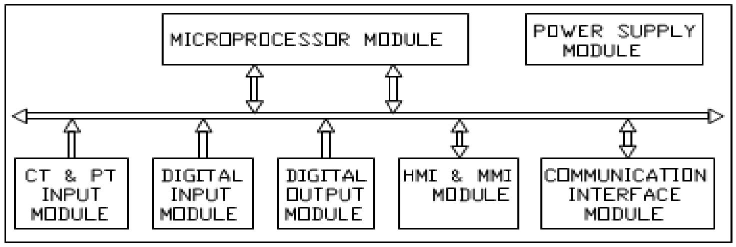

Figure 1. Hardware structure of numerical relay.

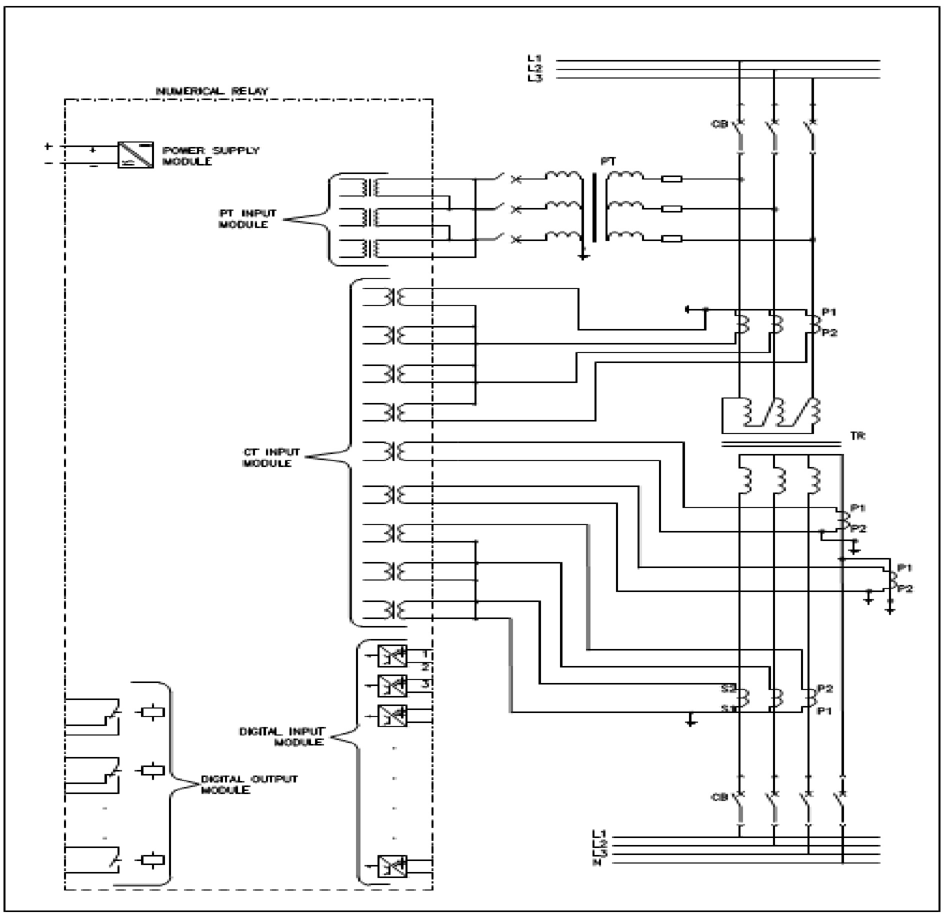

Figure 2. CT & PT connection of numerical relay.

E. Communication Module

Communication module consists of serial link interfaces for communicating measured electrical parameters, fault status, inputs given in digital input module, etc. Communication module also used to receive the command from PMS/SCADA to open/close the transformer circuit breaker.

F. Microprocessor Module

Microprocessor module is connected to all the input modules, output module, HMI or MMI module and communication module. The microprocessor module receives the inputs from all the modules. The microprocessor module process this input like calculating the electrical parameters (kW, pf, etc), calculating positive, negative & zero sequence current, calculating differential current, calculating tripping time as per

IEC, etc. Based on the calculated values the microprocessor module closes/opens the relay contact provided in digital output module. Microprocessor module records the inputs, calculated values and the output performed. These recorded values can be viewed through HMI or through SCADA.

G. Power supply Module

Power supply module provides auxiliary power supply to the digital input module, digital output module, HMI or MMI module, Communication interface module and Microprocessor module.

III. PROTECTION FUNCTION PROVIDED BY NUMERICAL RELAY

Transformer is used in almost in all industries. Failure of transformer causes interruption of all process in plant. So it is very important to protect transformer from fault. The details of the numerical relay protection function and description about the fault occurring in transformer are discussed in Section IV to Section X.

IV. OVERCURRENT PROTECTION

Definite time overcurrent function and IDMT (Inverse Definite Mean Time) phase overcurrent function in numerical relay can be used to protect transformer from overcurrent. Both overcurrent protection functions can be used at same time. Overcurrent causes heating and damage the transformer. Overcurrent occurs due to overload and due to short circuit. IDMT overcurrent function (51) provided in transformer primary side numerical relay protects the transformer from overload and short circuit fault (refer Fig. 3). Both IDMT overcurrent protection function and definite time overcurrent function of numerical relay requires three CTs for measuring current in all phases. As shown in Fig. 2, three CTs at primary side of transformer are connected to numerical relay for measuring the current (same as CT connected to 50 and 51 at primary side of transformer shown in Fig. 10). Time setting multiplier, flux setting multiplier, type of overcurrent protection (IDMT or definite time) and type of IDMT (Normal inverse, Extremely inverse, etc.) shall be given as input to numerical relay. The measured phase currents are compared with IDMT characteristic by software. When the current exceeds the pickup setting and inverse time, the relay trips the breaker to protect the transformer.

The setting of IDMT function of numerical relay provided in primary side shall not trip for transformer inrush current and transient overreach. Pickup setting of 100% of rated current may trip breaker without fault because of inrush current and transient overreach. IEC transformer rated less than 100 MVA can withstand 1.5 times of full load current (cyclic loading). IEC transformer rated more than 100 MVA can withstand 1.3 times of full load current [1]. The pickup setting of IDMT function of numerical relay shall be in between 125% to 150% of rated current. In case pickup setting required for 100% or less than 100% of rated current Numerical relay with IDMT overcurrent function shall be provided at secondary side of transformer (as shown in Fig. 3). Secondary side overcurrent function of numerical relay requires phase CT input of all phases like primary side numerical relay. IEC transformers withstands symmetrical short-circuit current for 2 seconds [2]. Setting provided in numerical relay for IDMT curve shall not exceed these values.

Definite time overcurrent function of numerical relay with time setting as zero acts as instantaneous overcurrent relay (50). Instantaneous overcurrent protection provided by numerical relay used to protect short circuit fault on primary side of transformer. Instantaneous overcurrent relay can provides fast tripping at higher fault current. Pickup setting of instantaneous overcurrent relay shall withstand inrush current and transient overreach. In secondary side of transformer, the fault current flows in transformer’s secondary side breaker and downstream breaker (downstream breaker to transformer’s secondary side breaker) is same for the fault occurred at the zone of protection of downstream breaker. Transformer secondary side breaker has to coordinate with downstream breaker. Hence on secondary side of transformer, instantaneous overcurrent relay cannot be used.

In ETAP, 33/6.9 kV solidly grounded Dyn11 transformer is modelled. Once the fault occurs on secondary side of transformer, the fault current started flowing in secondary side of transformer and primary side of transformer. These primary side fault currents and secondary side fault currents (due to fault on secondary side) are calculated for the modelled transformer based on IEC 60909 using ETAP. The results of ETAP model is shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 12. For the three phase symmetrical fault on secondary side of transformer, the fault current on three phases of primary and secondary side of transformer is shown in Fig. 4. For line to line fault on secondary side of transformer, the fault current on three phases of primary and secondary side of transformer is shown in Fig. 5. For phase to ground fault on secondary side of transformer, the fault current on three phases of primary and secondary side of transformer is shown in Fig. 6. For phase

to ground fault on secondary side of transformer, the positive sequence, negative sequence and zero sequence current on primary and secondary side of transformer is shown in Fig. 12.

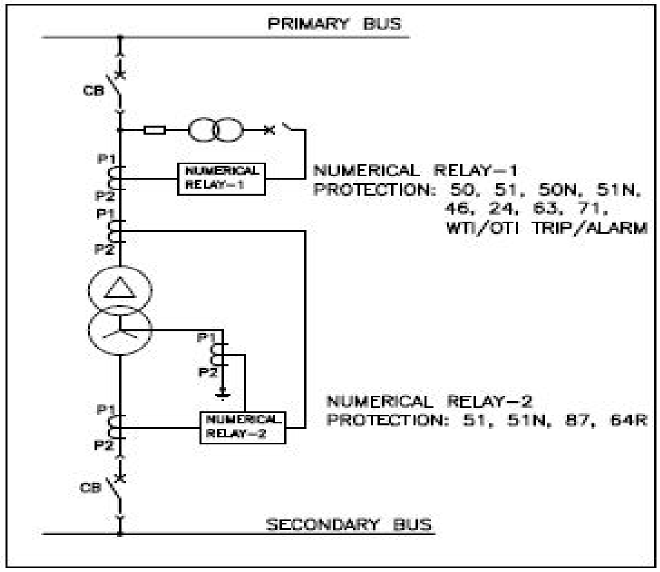

Figure 3. Single line diagram showing connection of Numerical at primary & secondary side of transformer.

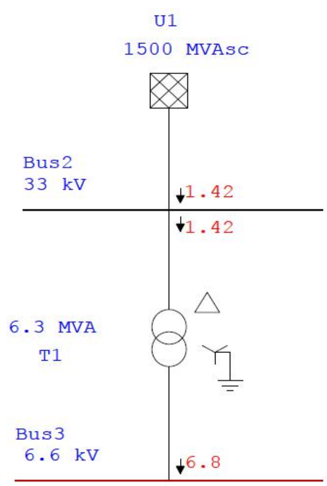

Figure 4. For Star-delta transformer (with delta as primary connection) symmetrical three phase fault current calculated using ETAP

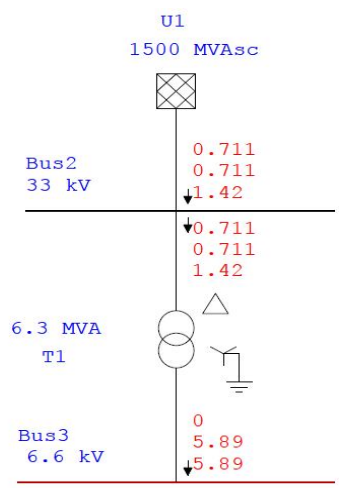

Figure 5. For Star-delta transformer (with delta as primary connection), Line to line fault current calculated using ETAP

In solidly grounded star-delta transformer the single phase to ground fault is higher than or equal to three phase symmetrical fault current. For three phase fault at secondary side of transformer shown in Fig. 4, the three phase symmetrical fault current in primary side is 1.42 kA (12.9 p.u.) and in secondary side is 6.8 kA (12.9 p.u.). For the single phase to ground fault at secondary side of transformer shown in Fig. 6, the primary side fault current at two phases is 0.887 kA (8.04 p.u.) and secondary side fault current at the faulted phase is 7.35 kA (13.94 p.u.). The secondary side fault current for single phase to ground fault is 108% (13.94x100/12.9) of symmetrical three phase fault current. Normally single phase to ground fault current is 100% to 111.11% of symmetrical three phase fault current [3]. If single phase to ground fault is higher than three phase symmetrical fault then single phase to ground fault shall be considered for coordination study and overcurrent function setting of numerical relay instead of three phases to ground fault.

In Fig. 6, the fault current at primary side due to single phase to ground fault at secondary side is 62.47% (0.887x100/1.42) of fault current at primary side due to three phase symmetrical fault at secondary side (refer Fig. 4). Normally this value varies from 57.71% to 64.21%.

In Fig. 6, the fault current at two phases of primary side is 57.71% (8.04x100/13.94) of fault current at secondary side. In other word, 804% of rated current flows at primary side and 1390% of rated current flows in secondary side. For this condition the IDMT overcurrent function of numerical relay at primary side takes more time to clear the fault. Hence overcurrent protection function of numerical relay at primary side cannot provide protection for phase to earth fault at secondary side.

For line to line fault at secondary side of transformer shown in Fig. 5, the fault current at one of the phases at primary side is 1.42 kA (12.9 p.u.) and it is equal to primary side fault current due to symmetrical three phase fault at secondary side (shown in Fig. 4). The fault current in other two phases at primary side is 0.711 kA (6.45 p.u.). The secondary side fault current at two phases is 5.89 kA (11.17 p.u.). Hence for line to line fault at secondary side, the primary side fault current at one of the phase is 115.3% (12.9x100/11.17) of secondary side fault current [4]. Due to this condition primary side numerical relay may operate before secondary side numerical relay. For line to line ground fault, the primary side numerical relay setting shall be checked for proper coordination.

In ETAP, 33/6.9 kV Yd11 transformer is modelled. The primary side fault current and secondary side fault current (due to fault on secondary side) is calculated for the modelled transformer based on IEC 60909 using ETAP. The results of ETAP model is shown in Fig. 7 and Fig. 8. For the three phase symmetrical fault on secondary side of transformer, the fault current on three phases of primary and secondary side of transformer is shown in Fig. 7. For line to line fault on secondary side of transformer, the fault current on three phases of primary and secondary side of transformer is shown in Fig. 8. The fault currents in Fig. 7 are same as Fig. 4 and the fault currents in Fig. 8 are same as Fig. 5. For this transformer connection also the IDMT overcurrent function of numerical relay at primary side shall coordinate with secondary side numerical relay.

V. Differential Protection

Overcurrent protection function of numerical relay provided at primary side of transformer cannot discriminate internal and external short circuit. Instantaneous overcurrent function of numerical relay on primary side of transformer can be used to detect and protect the internal short circuit current greater than transformer inrush current and transient overreach. Instantaneous overcurrent protection function (definite time overcurrent function with time setting of zero) of numerical relay at primary side can’t protect the

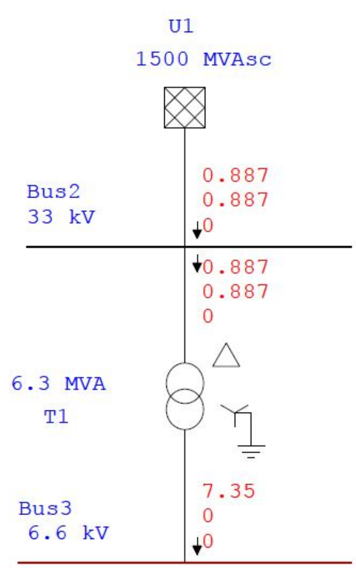

Figure 6. For Star-delta transformer (with delta as primary connection), phase to ground fault current calculated using ETAP.

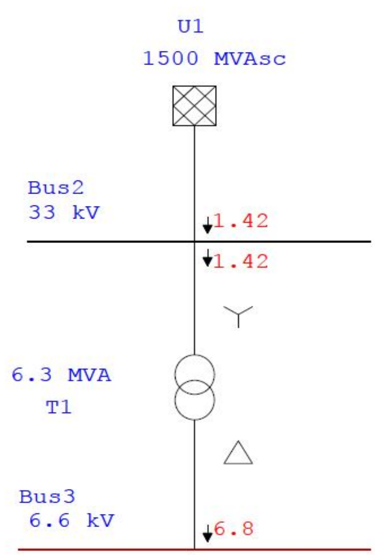

Figure 7. For Star-delta transformer (with star as primary connection), symmetrical three phase fault current calculated using ETAP.

transformer from internal fault at secondary side. Also instantaneous overcurrent function of numerical relay can't provide protection for sensitive internal fault current at primary side. Hence differential protection shall be provided to protect the transformer from internal fault.

Numerical relay with biased differential protection function or high impedance differential protection function can be used to provide differential protection of transformer. Interposing CT for compensating turn ratio of transformer and 30^{O} phase shift compensation for star-delta transformer are not required for numerical relay. Both primary side CT and secondary side CTs are connected in star connection. Transformer primary voltage, secondary voltage, primary and secondary CT ratio needs to be given as input to numerical relay. The transformer turns ratio and 30^{O} phase shift for star-delta transformers are compensated in relay microprocessor module.

The operating characteristic for biased differential protection is shown in Fig. 9. Biased current (average of transformer primary and secondary current) is taken in X-axis and differential current is taken in Y-axis. Differential current at no load I_{base}, slope m_1 and slope m_2 are given as input setting to numerical relay. The area under the curve is safer zone and relay does not operate. The area above graph is faulty zone and numerical relay operates to protect transformer.

The setting for I_{base} shall avoid tripping because of current mismatch due to No-load current. Setting for slope m_1 shall avoid tripping because of current mismatch due to CT error and load tap changer. Setting for slope m_2 shall avoid tripping because of current mismatch due to CT saturation during external fault at secondary side. The setting of I_{base}, m_1 and m_2 shall be a minimum for better protection of transformer.

VI. EARTHFAULT PROTECTION

For earth fault current, IDMT earth fault overcurrent protection function (51N) & definite time earth fault overcurrent function available in numerical relay provides sensitive protection than phase overcurrent protection function of numerical relay. Definite time earth fault overcurrent protection function with time setting as zero can be used as instantaneous earth fault overcurrent protection function (50N or 50 G). In low resistance grounding phase overcurrent protection of numerical relay can't provide protection for ground fault current. In transformer, primary side earth fault protection can be obtained by IDMT earth fault overcurrent protection function (51N) and instantaneous overcurrent protection function (50N) of numerical relay as shown in Fig. 3. For IDMT earth fault overcurrent protection function and instantaneous overcurrent function, residually connected CT secondary need to be connected to numerical relay as shown in Fig. 2 (same as 50N & 51N connection show at primary side of transformer in Fig. 10). Alternatively CBCT can be connected to numerical relay instead of residually connected CT secondary for earth fault protection of transformer at primary side (refer Fig. 11). If CBCT is connected to numerical relay then instantaneous earth fault overcurrent function (50G) shall be provided at primary side and IDMT earth fault overcurrent function shall not be provided. Numerical relay requires pickup setting as input for instantaneous earth fault setting and Numerical relay requires pickup and time setting as input for IDMT earth fault setting. Numerical relay measures the zero sequence current at primary side of transformer either through residually connected CT secondary or through CBCT. Once the zero sequence current exceeds the pickup and time setting, numerical relay trips the transformer primary side breaker and protects transformer.

For star-delta transformer, the primary side IDMT overcurrent protection function of numerical relay (51) cannot provide protection for phase to earth fault at secondary side (Section IV). The primary side earth fault overcurrent protection function of numerical relay (50N/51N and 50G) also cannot provide protection for phase to earth fault at secondary side because no zero sequence current flows on primary side of transformer for single phase to ground fault on secondary side (refer Fig. 12).

For transformer secondary side, earth fault protection can be obtained by providing IDMT earth fault protection function (51G) of secondary side numerical relay as shown in Fig. 3. The CT between neutral and grounding at secondary side of transformer shall be connected to numerical as shown in Fig. 2 (same as CT connected to 51G at secondary side of transformer in Fig. 10). IDMT earth fault overcurrent protection function of numerical relay at secondary side of transformer can coordinate with downstream relay. IDMT earth fault overcurrent protection of numerical relay can detect internal and external earth fault at secondary side of transformer. Same as primary side IDMT earth fault protection function (51N) secondary side IDMT earth fault overcurrent protection function requires pickup and time setting as input. Once the earth fault current exceeds the pickup and time setting numerical relay trips the transformer secondary side breaker. Intertripping function shall be provided in secondary side switchgear to trip transformer primary side breaker during fault at secondary side.

VII. RESTRICTED EATHFAULT PROTECTION

IDMT earth fault overcurrent function of numerical relay at star side of transformer cannot discriminate between internal and external earth fault. Hence numerical relay with restricted earth fault protection function (64R) can be used (as shown in Fig. 3) for fast tripping on internal earth fault. For restricted earth fault protection 3 Nos. of CTs in phase and 1 No. of CT in neutral is required. But in numerical relay the 3 Nos. of phase CTs used for overcurrent protection can be used for restricted earth fault protection phase CTs. Only one additional neutral CT is required for numerical relay for restricted earth fault protection. In Fig. 2, the neutral CT provided at secondary side of transformer is connected to numerical relay for restricted earth fault protection (same as neutral CT connected to 64R shown in Fig. 10). In transformer with 3 phase four wire system, the neutral current and ground fault current shall flow through the CT at the neutral (refer Fig. 10).
Biased restricted earth fault protection characteristic (biased by maximum phase current) is same as biased differential protection (refer Fig. 9). Base current I_{base}, slope m_1 and slope m_2 are given as input setting to numerical relay for restricted earth fault protection (Refer Section V for more details).

VIII. PROTECTION FOR OVERFLUXING

Overfluxing can be protected by using V/Hz function (24) of numerical relay. Overfluxing in transformer occurs while voltage increases abnormally at power frequency. Due to overfluxing, core material gets saturated during part of each half cycle [5]. The magnetising current increases at the primary side of

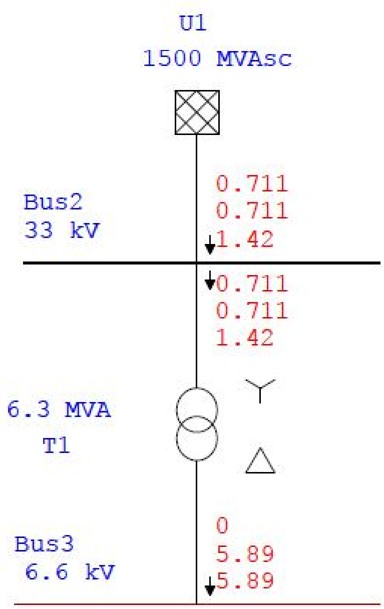

Figure 8. For Star-delta transformer (with star as primary connection), Line to line fault current calculated using ETAP

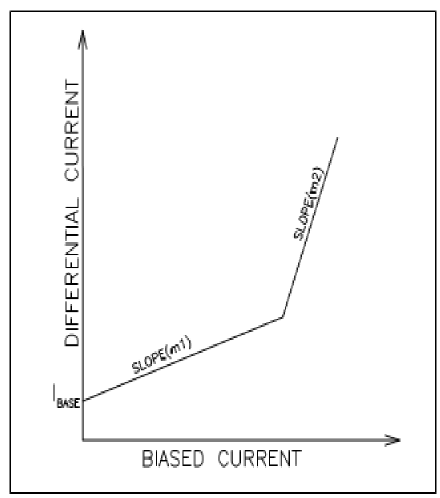

Figure 9. Characteristic of differential protection

transformer and flux increases (but the flux don't increase in proportional to the magnetising current during core saturation). The iron loss increases and the core get heated up and damage can occur to transformer. Transformer can withstand the ratio of voltage to frequency of 105% [6].
Due to load rejection on generator, overfluxing occurs in transformers directly connected to generator. Due to Ferranti effect, overfluxing may occur in transformers connected to long transmission line. Transformers connected to remote generating station through long transmission line will experience a severe overfluxing due to load rejection on generator and Ferranti effect [4].
The secondary voltage will not be proportional to primary voltage because the flux doesn't increases in proportional to magnetising current (if core is saturated). The secondary voltage will be lesser than product of primary voltage and turns ratio. Hence in Fig. 3, V/Hz protection function (24) provided in numerical relay at primary side of transformer. The voltage and frequency are measured through PT input module. The

connection of PT with numerical relay for measurement of voltage and frequency is shown in Fig. 2. V/Hz ratio is calculated in microprocessor module. Once the V/Hz ratio exceeds the pickup and time setting, the numerical relay trips the primary side breaker and protects the transformer.
In numerical relay, V/Hz protection function follows IEC IDMT curve. Definite time trip is also available for V/Hz protection. Numerical relay requires pickup and time setting as input for IDMT curve and definite time protection. The transformer capability for overfluxing shall be obtained from transformer manufacturer. Based on that, pickup and time setting of V/Hz relay shall be provide to numerical relay.

IX. NEGATIVE PHASE SEQUENCE RELAY

Numerical relay can provide negative phase sequence overcurrent function (47) as a backup protection for single phase to ground fault at secondary side of star delta transformer. In star-delta transformer, phase overcurrent protection function of numerical relay and earth fault overcurrent protection function of numerical relay at delta side cannot provide protection for single phase to ground fault at star side (refer section IV & VI). Earth fault overcurrent function of numerical relay at star side can provide protection for single phase to ground fault at star side. But there is no backup protection at delta side of transformer for single phase to earth fault at star side.
Negative phase sequence current flows in delta side of transformer for single phase to ground fault at star side (refer Fig. 12). Hence negative phase sequence overcurrent function of numerical relay can be used as back up protection for the earth fault relay at star side of transformer.
Numerical relay measures the three phase current through the CT input module. The negative phase sequence current is calculated by numerical relay at the processor module. When the negative phase sequence current exceeds the pickup and time setting, then the numerical relay clears the fault and protects the transformer. The negative phase sequence relay shall coordinate with star side earth fault relay.
In numerical relay, negative phase sequence protection follows IEC IDMT curve. Definite time trip is also available for negative phase sequence protection. The pickup and time setting shall be choose such that for secondary side single phase to earth fault current doesn’t exceed 2 seconds.

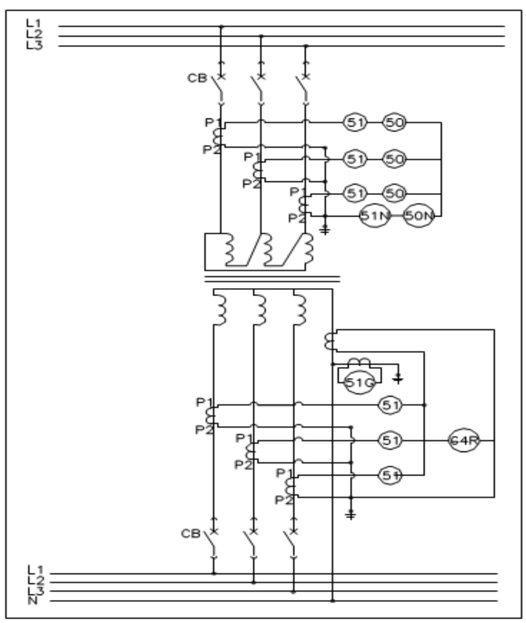

Figure 10. Three line diagram showing overcurrent, earth fault & restricted earth fault protection (analogy to numerical relay connection).

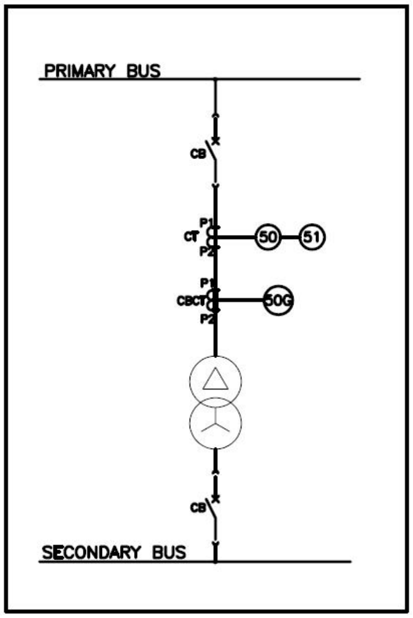

Figure 11. Single line diagram showing overcurrent & earth fault protection at primary side using CBCT and 50G

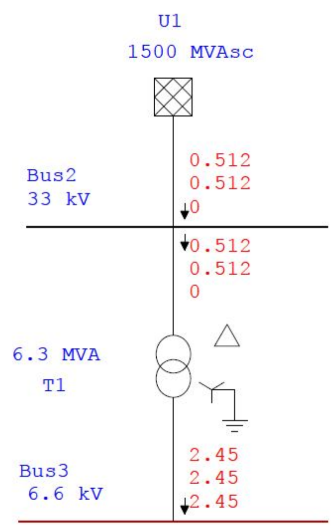

Figure 12. For Star-delta transformer (with star as primary connection), positive, negative & zero sequence fault current (for single phase to ground fault at secondary side) calculated using ETAP

X. Communication of Bucholtz Relay, WTI, OTI & MOG Status

The alarm contacts of bucholtz relay (63), Winding Temperature Indicator (WTI), Oil Temperature Indicator (OTI) and MOG (Magnetic Oil Gauge, device number 71) are wired to digital input module of numerical relay. The trip status contact of the bucholtz relay, WTI and OTI are wired to digital input module of numerical relay. These alarm and trip status are communicated to PMS / SCADA.

Some numerical relays have RTD (Resistance Temperature Detector) input module for measuring temperature. The winding temperature RTDs and oil temperature RTDs provided in transformer are connected to RTD input module of numerical relay. The microprocessor module records the measured the winding temperature and oil temperature. The microprocessor module compares the measured value with set value. If the recorded value exceeds the sets value numerical relay trips the secondary side and primary side breaker to protect the transformer. Also the microprocessor module communicates the measured temperature and trip status with PMS/SCADA.

XI. Control And Operation

Numerical relay can close and open the CB through PMS / SCADA. For closing and opening of CB, the auxiliary contact of CB (for CB close and CB open status) and auxiliary contact of lockout relay (for CB fault status) need to be wired to digital input module of numerical relay. If required, transformer trouble status (winding temperature alarm, oil temperature alarm, etc.) shall be wired to digital input module. Microprocessor module records these CB close, CB open and CB trip status.

One relay contact (NO contact) of the digital output module need to be wired to closing circuit (for closing CB) and another relay contact (NO contact) of the digital output module need to be wired to tripping circuit (for opening CB).

Numerical relay communicates the CB closed, CB open and CB fault status to PMS/ SCADA and receives CB open and close command from PMS / SCADA via communication module (refer Fig. 1). The communication protocols available such as MODBUS TCP/IP, profinet, Ethernet / IP, IEC 61850, etc. Based on the command received, the microprocessor module checks CB closing logic / opening logic condition and operates the relay contacts of digital output module. For example, microprocessor module receives close command from SCADA and checks the CB closing logic condition (like whether CB open or not, CB faulty

or not, etc.) and operates the relay contacts (if CB is open, if CB is not faulty, etc.) connected to closing circuit.

XII. SUMMARY

For green field projects numerical relays are preferred over electromechanical relay. In this paper the advantages of numerical relay, hardware structure of numerical relay, protection function provided by numerical relay for transformers and control & operation of transformer using numerical relay are discussed in Section I to Section XI.

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